THE DEVELOPMENT OF NASA'S LOW THRUST TRAJECTORY TOOL SET

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INTRODUCTION

Background

- Highly efficient electric propulsion systems can enable interesting classes of missions; unfortunately, they provide only a limited amount of thrust.
- Low-thrust (LT) trajectories are much more difficult to design than impulsive-type (chemical propulsion) trajectories.
- Previous low-thrust (LT) trajectory optimization software was often difficult to use, often had difficulties converging, and was somewhat limited in the types of missions it could support.
- A new state-of-the-art suite ("toolbox") of low-thrust (LT) tools along with improved algorithms and methods was developed by NASA's MSFC, JPL, JSC, and GRC to address the needs of our customers to help foster technology development in the areas of advanced LT propulsion systems, and to facilitate generation of similar results by different analysts.

Purpose

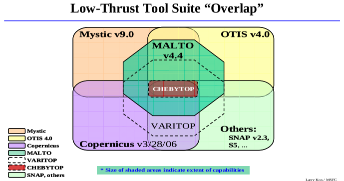
The purpose of this low-thrust trajectory optimization tool (LTTT) activity was to produce a tool or suite of tools that would allow the mission design community to do interplanetary low thrust trajectory analyses that:

1. would be consistent (between various NASA centers and between various analysts);
2. would be easier to use, converge more robustly, and handle more intermediate encounters than legacy software;
3. could be quick turn-around at times when needed (e.g. in hours or days); and,
4. would have analysis fidelity levels that could be partially "selectable", determined by time allowed.

Primary Features:

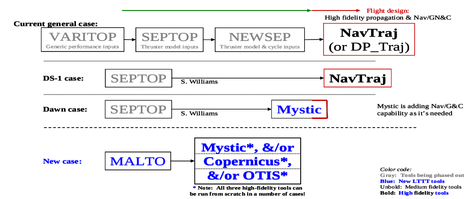
- Previous low thrust (LT) trajectory optimization software was often difficult to use, often had difficulties converging, and was somewhat limited in the types of missions it could support.
  - New tools are higher fidelity than previous tools:
    - Level 0-1 tools -- Previous: CHEBYTOP (low) Current: MALTO v4.4 (mid)
    - Level 1-2 tools -- Previous: VARITOP (mid) Current: Mystic v9.0 (high) Current: OTIS v4.0 (high) Current: Copernicus v3/28/06 (high)
    - Level 1-2 tools -- Previous: SEPSPOT (mid) Current: SNAP v2.3 (high)
  - New tools are more user friendly than previous codes:
    - Previous tools -- CHEBYTOP, VARITOP: namelist input "decks"
    - Current tools -- MALTO, Mystic, Copernicus: Graphical User Interface (GUI)
  - New tools converge more easily than previous tools :
    - Previous tools -- VARITOP: often need previously converged input decks
    - Current tools -- MALTO, Mystic (initial guess "tool"), OTIS 4.0, SNAP, Copernicus
      - MALTO mid-fidelity tool converges easily, much like the low fidelity CHEBYTOP tool
      - Mystic converges much easier than VARITOP for cases without a previously converged case
      - Copernicus has interactive real-time 3D graphics & an initial guess estimator for basic missions
      - OTIS 4.0 has converged on cases using very poor initial starting points

Low-Thrust Tool Suite "Overlap"



DESIGN APPROACH AND METHODOLOGY

Steps in Low Thrust Trajectory Analyses



Interaction Within the Suite of Tools

- **MALTO:**
  - Medium fidelity tool to run initial trades/trade spaces with the option to give starting guesses to the high fidelity tools (below).
- **OTIS ⟷ Mystic ⟷ Copernicus**
  - Takes, as an optional method for starting, necessary inputs from the mid-fidelity tool to get going. Also, in the case of OTIS, an initial guess could come from a low fidelity tool (CHEBYTOP).
- **Future: High fidelity tools with "hooks" between them**

  Examples:
  - Mystic feeding an optimized mission/trajectory to OTIS for power and propulsion systems to optimize a vehicle
  - OTIS feeding an optimized power & propulsion systems result to Mystic to re-optimize a mission/trajectory with the subsystems considered

LTTT Tool Characteristics

LTTT Suite: Selection Criteria, Code Type, Additional Requirements & Availability

	JPL MALTO v4.4	JPL Mystic v9.0	JSC/UT Copernicus v3/28/06	GRC OTIS v4.0	GRC SNAP v2.3
Algorithm(s)	Impulsive ΔV Segments	Static & Dynamic/time controls/functions	Explicit Integration; Impulsive & Finite-burn ΔV segments	Implicit Integration	Numerical Integration
Main Optimizer	SNOPT	Static/Dynamic Control	SNOPT	SNOPT	n/a
GUI	Yes MATLAB*	Yes MATLAB*	Yes Winteracter/OpenGL	No	Yes Excelerator/Mac
Source Code	100% Fortran	100% Fortran	100% Fortran	100% Fortran	100% Fortran
SNOPT #	Yes #, v7.1-1.5	No	Yes #, v6.2	Yes #, v6.2	No
MATLAB*	Yes*	Yes*	No	No	No
Is it ITAR?	Yes ¤	Yes	No	Yes	No
Cost	Free	(1)	Free	Free	Free
Application (primary)	Low-thrust Interplanetary, some high thrust	Low-thrust Interplanetary, N-body	Low-thrust Interplanetary, N-body, & HT	Low-thrust Interplanetary, N-body, & ETO	Low-thrust Planetocentric, N-body, some helio.

* Additional license costs may be incurred for this add-on software package. Tools can be run in command line mode w/o MATLAB.
\# Additional license costs may be incurred for this add-on software package.
¤ Although there is no deep well, planet-centered trajectory targeting capability.
(1) Any governmental agency or anyone who is working under a government contract that requires the software can use it royalty free. Others may be charged a fee, depending on the desired use. The royalty for a commercial use license could be up to $100K for 5 years.

Low Thrust Trajectory Tool Beta Testing

Thirty-two reference missions were selected for beta testing to provide feedback to the developers, verify agreement between high fidelity tools, quantify variation between low, medium, and high fidelity tools, and establish a broad range of example cases for new users. The mission set was intended to capture future science missions and allow for full demonstration of low-thrust mission capabilities such as:

- Nominal interplanetary;
- N-body;
- Non-Keplerian orbits; and,
- Solar Electric Propulsion, Nuclear Electric Propulsion, Solar Sail, and variable specific impulse propulsion systems.

CONCLUSION

The intercenter team developed a suite of tools that are easier to use, higher fidelity, and converge more readily than previous tools. Additionally, the suite of tools cost nothing to qualified users/recipients (except in the commercial application of one tool). All of the tools provide for greater accuracy than previous tools by implementing higher fidelity modeling and/or trajectory propagation.

- MALTO is the only medium fidelity tool developed during this software development effort. It is intended to be the starting point for nearly all low-thrust trajectory and mission preliminary design studies. It is designed to run faster and with fewer inputs than a high fidelity tool. MALTO is the tool of choice for running trade studies with up to three independent variables (i.e. a three-dimensional trade-space). MALTO is also the only tool in the suite that is used to perform solar sail analyses.

- Mystic is one of three high fidelity tools with its niche being trajectory optimization of the entire trajectory or mission. Mystic is most applicable towards determining an overall optimum trajectory (e.g. minimum fuel or minimum trip time for a given propellant load) due to its unique optimizer called "Static/Dynamic Control" (SDC).

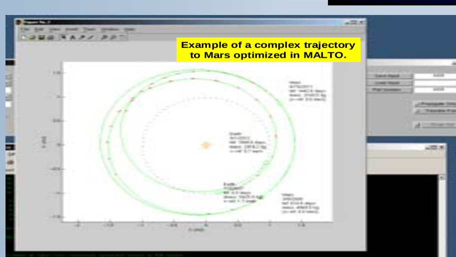
- Copernicus is another high fidelity tool that utilizes segments to piece together a desired mission trajectory. The available options for segments, comprising a dozen different types, are: continuous thrust, coast, starting or ending impulses, etc., for example. A feature of designing trajectories with a set of predefined segments allows a mission to be modeled with multiple propulsion systems, including high thrust, low thrust, and variable thrust, and also allows the user to enforce such constraints as crew wake/sleep cycles that apply to human missions.

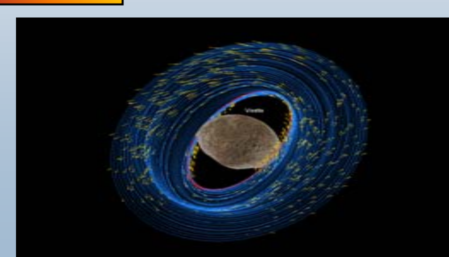
- OTIS v4.0 is now fully intended to be used as a high fidelity heliocentric analysis tool as well as its more commonly known use for Earth-to-orbit analyses. It is easier to use with the simplified input scheme and utilizes new mathematics (using collocation and pseudo-spectral methods as selectable options). OTIS carries forward from older versions the capability to model propulsion systems at a higher level of fidelity, thus providing for sizing at the subsystem and component level.

- SNAP is the only tool in the suite that focuses primarily on planet-centered analyses. It is a high fidelity propagator which accepts various types of pointing control laws to determine fuel, time, and path requirements. Simple heliocentric trajectory analyses can also be done with SNAP.

Visit our website for central communication by users at:
http://www.inspacepropulsion.com/LTTT/

EXAMPLE RESULTS





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